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Long-term bridge health monitoring focusing on the Mahalanobis Distance of modal parameters

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Abstract. Maintaining civil infrastructure, including bridges, has been a keen technical issue in developed countries and will surely be one in developing countries in the near future. An effective maintenance strategy strongly depends on timely decisions on the health condition of the structure. Bridge health monitoring (BHM) using vibration data is widely recognized to be one of the effective technologies that aid decision-making on bridge maintenance. This research focuses on long-term BHM expecting that changes in physical properties of the bridge subject to aged-deterioration progress slowly. In the practical application of the long-term BHM, one of the difficulties is that the observed vibration data includes environmental influences such as temperature change. In order to achieve high accuracy in evaluating modal parameters of the bridge, other influencing variables have to be taken into consideration. In this study, temperature is considered as the main environmental factor by means of a regression analysis. The Mahalanobis distance (MD), a multivariate statistical distance, is adopted to emphasize potential changes in the identified modal parameters. The validity of the proposed approach is investigated utilizing vibration data measured at a real bridge in service.

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1. Introduction

Damage in bridges has been reported in many countries due to deterioration, aging, heavy loads, etc. How to establish an economical and efficient structural soundness evaluation system has been a keen issue in the field of civil engineering for years. As a strong tool, long-term bridge health monitoring by observing change in bridge vibration characteristics is attracting wide attention.

Theoretically, damage in the bridge is supposed to change the way the bridge vibrates and thus be quantitatively reflected in the change in modal parameters of the bridge. However in the practice of long-term bridge health monitoring, environmental factors also exert influences on modal parameters. Consequently, how to remove the environmental disturbances and extract the change in modal parameters due to damage in the bridge is a major challenge. In this study, regression method is adopted to eliminate the environmental effect.

There have been attempts for damage detection focusing on changes in modal parameters in the past as well [e.g. 1]. One of the difficulties is that before damage occurs, it is difficult to predict which modal parameter is the most sensitive to change in the dynamic characteristic of the bridge. Moreover, even if there appear changes in some of the modal parameters, the level of change in each single modal parameter is usually too small for judging whether they are due to the occurrence of damages in the bridge or just regular fluctuation. Therefore to overcome these difficulties, it is attempted in this study to integrate the information of multiple modal parameters into a single indicator, the Mahalanobis distance, for damage detection.

This study, at first, is intended to identify the modal parameters of a real bridge from monitoring data utilizing single-variate auto-regressive model. Then, a linear regression method is adopted to eliminate influence of environmental factors from modal parameters. After transforming modal parameters, the Mahalanobis distance is calculated and utilized as the damage-detecting indicator for structural diagnoses of bridges. In order to verify validity of the proposed approach, the monitoring data taken from a real bridge, including the data recorded during a traffic accident are utilized.

2. Damage-detecting indicator

The Mahalanobis distance (hereafter MD) is a generalized distance, which can be considered as a single-dimensional quantity that expresses the degree of divergence of a multivariate sample with respect to the central point of the set of normally distributed multivariate samples it belongs in considering the correlations between the variables. MD is a quite useful way for determining the similarity of a set of values from an unknown sample to a set of values measured from a collection of known samples [2]. In this study, the unknown sample is the modal parameters of the target span of the bridge of interest identified when whether damages have occurred is unknown and the known samples are those identified when the bridge was assumed to be healthy. By estimating MD of a certain observation point, the similarity of the vibrational properties at that time to the intact ones can be quantitatively expressed, which is focused at for damage-detecting in this study. Another advantage of adopting MD as the indicator is that it contains the information of multiple variables, the modal parameters, which vary in a level that is not obvious enough to draw conclusion about the existence of damages, and by accumulation, minimal changes in modal parameters due to change in vibration characteristics during long-term monitoring become noticeable difference in MD, which makes it easier for decision-making. Detailed mathematical derivation is interpreted in **4.1**.

3. Real bridge monitoring

3.1. Target bridge

The monitoring data used in this study was taken from the first span from the west of a seven-span plate-Gerber bridge, which was constructed in March, 1960 and has been in service for over 50 year. The photographs of the target bridge and monitored span are shown in **Figure 1** and **Figure 2** respectively and the main information of the bridge are summarized in **Table 1**. In 2004, as a preventive measure against material fatigue, the beam end was strengthened and bridge slab was reinforced by increasing the thickness. Furthermore, considering the bridge is located in a highly occupied national road where around 60% of passing vehicles are heavy trucks, structural monitoring was thought to be necessary.

3.2. Sensors

Monitoring data used in this study are ambient vibration data and temperature data, which are measured by four accelerometers (UA1, UA2, DA1 and DA2) and two thermometers (T-5 and T6). The locations of the sensors are shown in **Figure 3**. UA1 and DA1 were deployed near mid-span, where information of global vibration including 1st mode are relatively easy to extract, while UA2 and DA2 were deployed near the hinge, where deterioration and fatigue damages occurred.

Figure 1 The target bridge

Figure 2 The monitored span

Table 1 The main information of the bridge

Construction year		1960
Bridge length (m)		187.0
Span length (m)	Hanging girder	16.0
	Anchorage girder	6.2+28.4+6.2
Width (m)		8.0

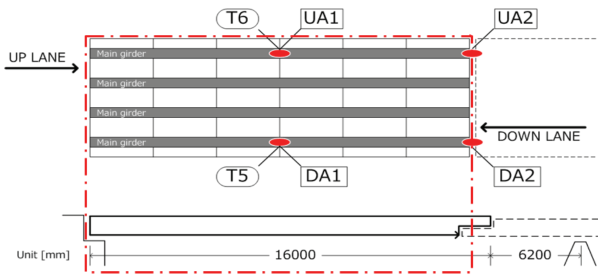

Figure 3 Sensor deploying map

3.3. Observation period

The monitoring started from August 2008 on a full-scale and is still continuing now. Due to hardware problem and operational mistakes, there exist several discontinuities during the six years so far. Though not continuous, available data are from August 10, 2008 to July 13, 2014 and they are all utilized in this study. Besides those, the data of October 18, 2007, on the morning of which a traffic accident took place on the monitored span of the bridge, is used to test the sensitivity of MD.

4. Long-term health monitoring focusing on the Mahalanobis distance of modal parameters

4.1. Derivation of damage detecting indicator
Detailed procedures for calculating MD are described in this subsection.

4.1.1. Identification of frequencies and damping constants. Identifying the system parameters from vibration data by means of linear time-series models such as auto-regressive (hereafter AR) model is a promising approach [3, 4]. Frequencies and damping constants were identified by means of a single-variate AR model from ambient vibration data measured at each sensor [5].

In view of huge amount of data, this study, by means of moving time windows shown in **Figure 4**, identifies modal parameters 200 times for each one hour of vibration data at each sensor. Each time, up to ten frequencies are generated as well as their respective damping constants, and their average values of 200 times are the output of the data of each hour. As it turned out from the results, frequencies near 4Hz and 10Hz are the dominant domains. Therefore, they, as well as their damping constants, were chosen to focus on.

4.1.2. Measures to remove environmental influences. Undoubtedly, the modal parameters identified in this way include environmental influences. In order to propose an indicator that only changes along with the bridge's structural soundness, disturbances of these exterior factors have to be removed.

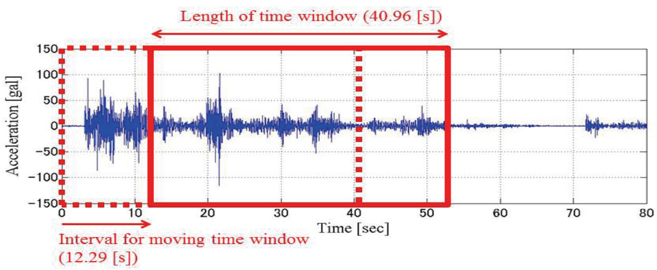

Figure 4 Time windows for identifying modal parameters

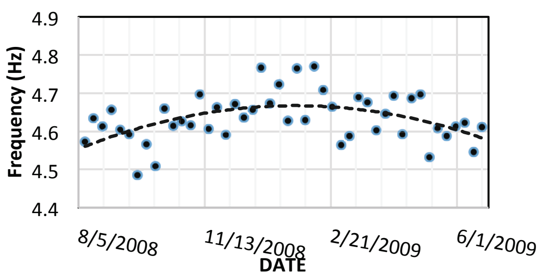

Figure 5 Frequency around 4Hz at DA1

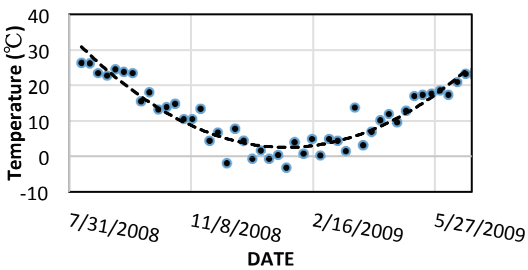

Figure 6 Yearly temperature of the bridge

Clear seasonal fluctuations were noticed in most of frequencies and damping constants. As an example, frequencies around 4Hz identified at DA1 from August 10, 2008 to June 21, 2009 are plotted in **Figure 5**. These seasonal changes were thought to be due to environmental factors, of which temperature was considered to be the most influential one in this case since temperature shows extremely similar but opposite rise and fall during the year, as shown in **Figure 6**. One of the possible reasons of this correlation could be the temperature-dependence of young's modulus of materials, as is also suspected as one of the main reasons in other studies [6]. Based on experiment results, both concrete and steel, which are the main materials of the target bridge, show minimal changes when temperature change [7, 8]. In order to verify whether these changes quantitatively match with those in natural frequencies, rough calculation was done. Theoretically, for the same system, natural frequencies are proportional to the Young's modulus of the system. As can be approximately estimated from **Figure 7** [7] and **Figure 8**, [8] when temperature increases from 0 ^{o}C to 30 ^{o}C, where temperature of the target bridge varies, Young's modules of steel and concrete decrease with about 0.9 percent and 1.6 percent respectively. Therefore, change in the equivalent Young's modulus should be between 0.9 percent and 1.6 percent. In the same temperature range, identified natural frequencies drop with around 2.5 percent in average. Considering the inaccurateness of the experiment result, it can be concluded that the temperature-dependences of young's modules of materials is one of the possible explanations for the correlation between natural frequencies and temperature. Further investigation is necessary before making more definite conclusion. As for damping constants, which slightly linearly increases as temperature increases, physical mechanism about the correlation remains unknown and future research ought to be done to understand it.

Due to the difficulty of accurately modeling temperature's impact, statistical approach was adopted to remove its influence. Since most modal parameters show linear relation with temperature, linear regression model was utilized in this study. Considering data from August 10, 2008 to June 21, 2009 are the closest to intact condition, regression coefficients were estimated with data in this period. Again, the procedure of this manipulation is illustrated taking frequency around 4Hz identified at DA1 as the example. Firstly, a linear regression model is established as below,

$$f = kT + C \tag{1}$$

where f and T stand respectively for frequency and temperature, and k and C indicate the regression coefficient and constant in respect.

By subtracting the temperature related term, kT, from the frequency data, it is transformed into a temperature-independent variable, as shown in **Figure 9**. The same procedure was done to all other modal parameters before progressing to calculating MD.

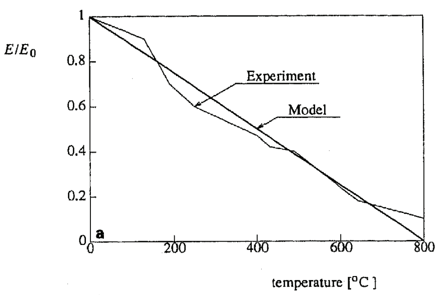

Figure 7 Young's modulus of concrete [7]

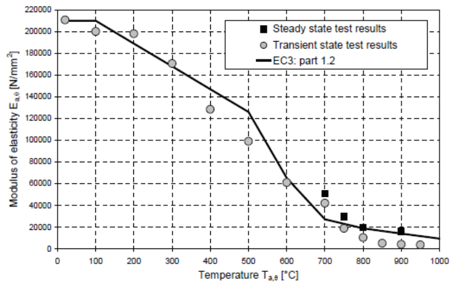

Figure 8 Young's modulus of steel [8]

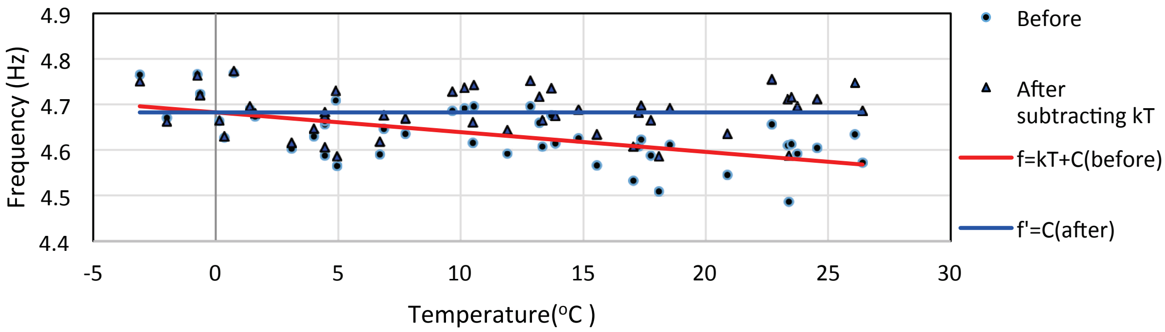

Figure 9 Frequency before and after removing temperature's influence

Another major environmental factor is the variation of passing vehicles. The correlation between natural frequencies of the target bridge and properties, such as volume, speeds and weights, of passing vehicles was proved by the result of data analysis in past study by Heng [9]. Since this study is the first attempt to utilize MD as the damage-detecting indicator, in order to simplify the problem, it is proposed to consider only one environmental factor, change in bridge temperature, during data analysis and minimize the influence of variation of passing vehicles by narrowing down data period. From the monitoring data, it was noticed that at 7 a.m. on Sunday mornings, amount of passing vehicles stabilizes in a relatively low level and shows small variation. On account of this, only data of this hour every week were chosen to be the objects for data analysis.

4.1.3. Estimation of Mahalanobis distance. Since it is generally known that accuracy of identification of frequencies from vibration data is higher than that of damping constants, frequencies were believed to be more suitable for detecting structural damage. Therefore, it was thought that MD calculated with frequencies only would be optimal. For comparison, analyses were also done for MD calculated with only damping constants and with both frequencies and damping constants.

This study attempts to detect damage by observing change in the vibration characteristics, therefore the reference data ought to be the intact modal parameters of the monitored span, which are data from August 10, 2008 to June 21, 2009 in this study for they are the closest to intact condition among available data. We here denote these reference data as a matrix, $A \in R^{k\times l}$, where l and k stand for number of reference data and number of variables respectively.

Firstly, all elements are normalized with,

$$B_{ij} = \frac{A_{ij}-m_i}{s_i},\ (i=1,\ldots,l;\ j=1,\ldots,k) \tag{2}$$

where m_i and s_i are the average value and standard deviation of the i-th column. Then, the correlation matrix, denoted as $C \in R^{l\times l}$, are formed with each element calculated with the following expression,

$$C_{ij} = \frac{1}{l}\sum_{n=1}^{l} B_{in}B_{jn}, \qquad (i = 1, \ldots, l;\ j = 1, \ldots, l) \tag{3}$$

Finally, for a normalized sample, $X \in R^k$, its MD can be calculated with the expression shown below[2],

$$MD = \left(\frac{1}{k}\right) X^T C^{-1} X \tag{4}$$

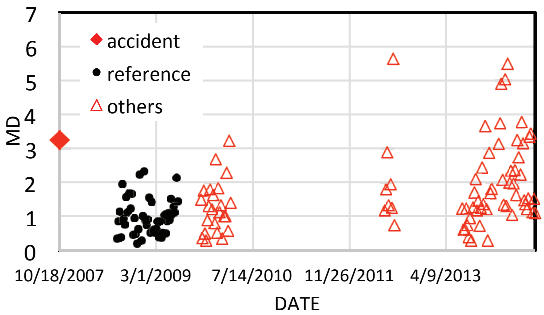

Figure 10 Case 1: *MD (f)*

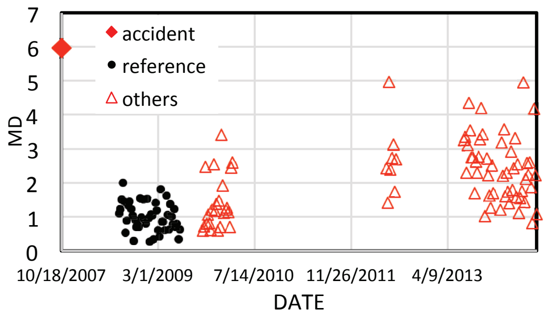

Figure 11 Case 2: *MD (d)*

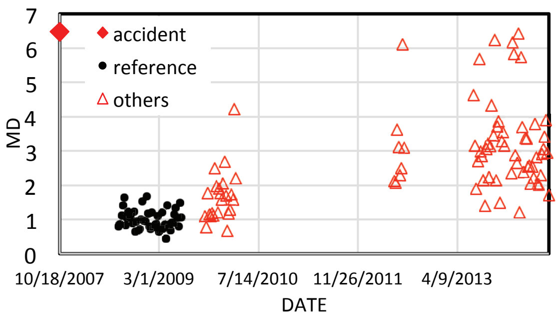

Figure 12 Case 3: *MD (f & d)*

Table 2 Results summary

Sensitivity to gradual change in vibrational characteristics	*MD (f&d)>MD(d)>MD(f)*
Sensitivity to abnormal (accident) data	*MD(d)>MD(f&d)>MD(f)*
Scale of fluctuation	*MD(f)>MD(f&d)>MD(d)*

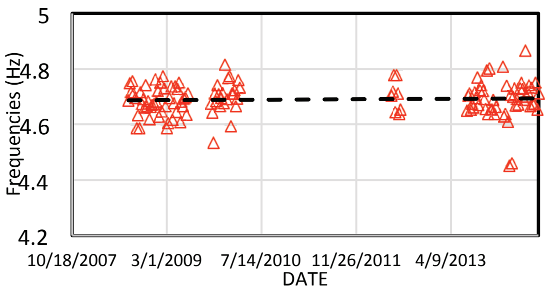

Figure 13 F4 at DA1

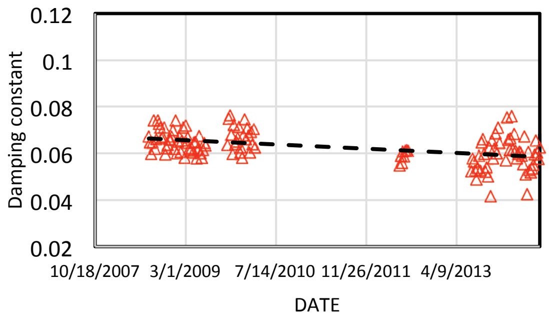

Figure 14 D4 at DA1

4.2. Application to long-term monitoring data

With MD as the indicator, data analysis is conducted with long-term monitoring data, including an abnormal data recorded in a traffic accident. With data from August 10, 2008 to June 21, 2009 as reference data, *MD*s of Case1, Case2 and Case3 are calculated for all data and plotted in **Figure 10**, **Figure 11** and **Figure 12** respectively. Therein Case1 considers MDs from the observed frequencies of all sensors near 4Hz and 10Hz, Case 2 considers MDs from the observed damping ratios of all sensors corresponding to the frequencies near 4Hz and 10Hz, and Case 3 considers MDs from both frequencies and damping constants of all sensors. In all three graphs, black points represent reference data. Red solid squares on the left of the graphs stand for accident data, and how large they are represent the sensitivity of each MD to abnormal data. And red triangles on the right represent unknown data, which are the rest of the monitoring data besides reference data. How much they deviate from reference data shows how sensitive each MD is to gradual structural change.

All three *MD*s showed noticeable increasing tendencies through the six years of monitoring.

Whereas, as shown by two examples of results of modal parameters in **Figure 13** and **Figure 14**, not all of them show obvious deviation from intact data.

5. Discussion

This study investigates the validity of utilizing Mahalanobis distance (*MD*) of modal parameters as the damage-detecting indicator for long-term bridge monitoring. Temperature, as the most influential environmental factor, was taken into consideration by means of regression method.

The proposed approach was applied to the long-term monitoring data of a seven-span plate-Gerber bridge. Conclusion drawn based on the results of this study could be summarized as follows: 1) all three *MD*s showed noticeable increasing tendencies through the six years of monitoring, which could imply the probability of occurrence of damage in the monitored span; 2) MD is useful for integrating information of multiple variables and amplifying minimal changes in modal parameters into more noticeable changes; 3) different from the prediction stated in 4.1.3, *MD* calculated with both frequencies and damping constants seemed to have the best quality to be used as the indicator, considering sensitivity to gradual change in vibrational characteristics, sensitivity to abnormal data, scale of fluctuation and accuracy of identification; and 4) with current results, *MD* showed potential usefulness for damage detection and thus is worthy of further investigation.

For improvement of accuracy, data of passing vehicles ought to be utilized as well in future research. Also, shortage in continuous monitoring data is one of the reasons why more definite conclusion couldn't be reached. Therefore, now that the bridge is still under long-term monitoring, this study will make further analyses with the long-term monitoring data to come. Last but not least, for the realization of practical application, concrete managing standards is necessary to be established for decision-making.

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